Factors Influencing Electrical Load Shape of Heat Pump Water Heaters

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Heat pump water heaters (HPWHs) continue to gain the attention of energy providers and policy makers as an efficient alternative to traditional equipment for the residential market. While the operation of individual HPWHs has been widely studied, limited resources exist for understanding the aggregated operation for a population of HPWHs. This study examines the electrical load shapes of HPWHs by site characteristics, using field data from 147 residential HPWHs in the Pacific Northwest (PNW) during 2018.

Field data consisted of HPWH power consumption in combination with a survey of site characteristics, including the general occupancy schedule, home occupancy count, HPWH manufacturer and location of water heater at the home. Segmenting the data set for each site characteristic, the results examine how these factors influence the combined electrical load shape of the HPWH population. In addition, multiple weeks of data were collected during the regional COVID-19 stay-at-home period for a subset of the water heaters in 2020. The stay-at-home data demonstrate how HPWH electrical demand may evolve as employees and students increasingly operate from home.

Background

Diversified end-use electrical load profiles are important for utilities, demand response aggregators and regional planners (for establishing baseline behavior to design and evaluate demand-side management programs, load forecasting to make better decisions regarding generation and load resource acquisition and transmission upgrades). Until a recent study was finalized in 2012,[1] the load shape profiles produced in the early 1990s by the End-Use Load and Consumer Assessment Program[2] were heavily used in the PNW. With end-use behavior and energy use regularly evolving, end-use load shapes should continue to be examined.

The results presented in this article focus on electrical load shapes of HPWHs for households in the PNW. Water heaters make up 14% of annual household energy consumption nationally, making them the second-largest energy use in the residential sector.[3] HPWHs have the potential to reduce the annual energy consumption of residential water heating by 60% when compared to electric resistance water heaters.[4] Energy providers and

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policy makers are increasingly interested in understanding HPWHs, as their adoption could offer efficient electric water heating.

Methodology

In 2017, an electric water heater study was initiated in the PNW across several electric utility service territories to understand the capabilities of Consumer Technology Association Standard 2045 (CTA-2045) enabled water heaters to provide load shifting for peak load management and harnessing renewable energy. This field study included 147 CTA-2045-equipped HPWHs installed in single-family residences throughout the PNW. CTA-2045-equipped units were able to provide data on water heater operation (e.g., power consumption, operating status, curtailment mode and communication status).[5]

Although CTA-2045 offers a pathway for the load control of water heaters, these commands were not used in the data set examining HPWH electrical load shapes. Baseline HPWH data (i.e., no load control) were collected throughout 2018 and during certain periods of 2019 and 2020. The primary 2018 data set used in the load shape analysis was collected evenly throughout the calendar year; however, Saturdays, Sundays and the last two weeks of December were excluded. The baseline CTA-2045 HPWH power consumption data, along with homeowner surveys, were used to examine factors influencing HPWH electrical load shapes.

Data Acquisition for HPWH Power

HPWH power consumption data were collected at one-minute intervals, using universal communication modules that were physically connected to the water heaters through the CTA-2045 port with data transmission occurring over Wi-Fi. To evaluate the reliability of the CTA-2045-reported data, a subset of HPWHs were monitored with power meters capable of measuring true power with a rated accuracy of 1%.

The field study used two HPWH manufacturers and product models. CTA-2045-reported power data for one HPWH manufacturer, accounting for ~80% of the HPWHs in the study, demonstrated an agreement of 1.5% with the true power meter measurements.

The second HPWH manufacturer, accounting for the remaining ~20% of field systems, reported preprogrammed values based on the HPWH mode. Correction factors were applied to the CTA-2045 power data of this manufacturer based on the subset monitored for true power. These correction factors adjust the CTA-2045 HPWH power data for a yearly average perspective, and the adjustment does not account for seasonal changes. The HPWHs with corrected power data (~20% of population) was not included in the seasonal impact segmentation.

Homeowner Survey

A multiple-choice homeowner survey was conducted in 2018 for the HPWH field sites. The homeowner survey included questions on general occupancy schedule, occupancy count, heat pump water heater manufacturer and location of the HPWH in the home. In the survey, the general occupancy schedule was determined by asking, "Does at least 1 adult not work outside of the home for 4+ days a week?" Home occupancy count was collected in whole-number increments of 1, 2, 3, 4 or 5+.

The HPWH manufacturer data were collected as either one of two HPWH brands that offered CTA-2045 compatibility during the study, and the brand name was generalized to "Manufacturer A" and "Manufacturer B." The location of the HPWH in the home was collected as "garage," "basement" or "other" in the homeowner survey. Results from the survey are presented in *Table 1*.

TABLE 1 Site characteristics from 2018 homeowner survey.

Total Field Site Count	147 HPWHs
Average Home Occupancy	2.9 Occupants
1–2 Occupancy Count	49%
3+ Occupancy Count	51%
Adult(s) Stay at Home Regularly	65%
All Adults Leave Home Regularly	35%
Manufacturer A	20%
Manufacturer B	80%
Water Heater Located in Garage	67%
Water Heater Located in Basement	17%
Water Heater in Other Location	16%

Data Analysis

The data collected in this field study showed significant variations in electrical demand of individual HPWHs. However, the average power use across many water heaters is most useful to researchers and utilities alike for predicting energy consumption. In this study, an electrical load shape refers to a representative daily HPWH power profile, which is determined through averaging the hourly data of the underlying data set for each hour of the day. A load shape represents the daily average power profile for a given perspective. Using the HPWH power consumption data from the 2018 field study, a 24-hour

FIGURE 1 2018 baseline HPWH electrical load shape.

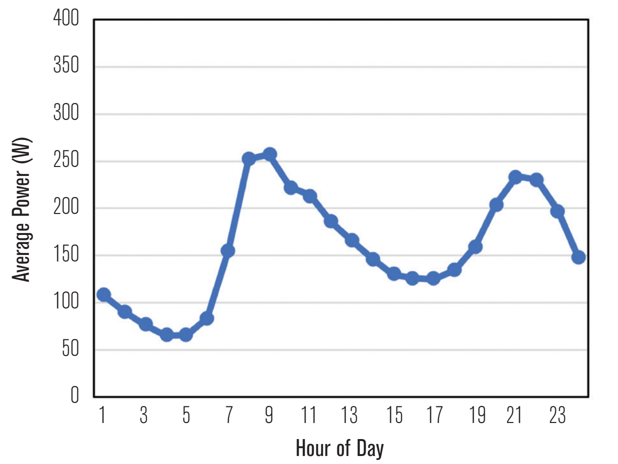
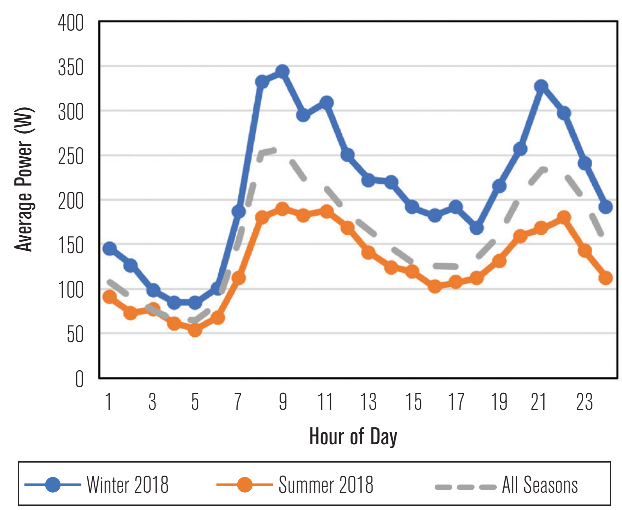


FIGURE 2 HPWH electrical load shapes by season.



HPWH power profile was determined for each individual HPWH (147 individual 24-hour profiles).

Segmentation analysis is then used to categorize the HPWH field sites based on occupancy count, HPWH manufacturer and occupancy schedule. For each segmentation, the individual site load shapes were aggregated to produce a load shape for each site characteristic. The aggregated HPWH power profiles were examined for their general shape, HPWH energy use and peak demand.

In Spring 2020, the COVID-19 pandemic presented a unique opportunity to study how power consumption would change as homes were more regularly occupied throughout the day. Oregon, where a significant number of sites were located, issued Executive Order No. 20-12 on March 23, 2020, which mandated a stay-at-home order.[6] During 2020, only 49 of the original 147 sites remained active in the field study. The Spring 2020 (stay-at-home) profile was compared to a Spring 2018 (pre-COVID-19) profile for a matching subset of HPWHs. The Spring 2019 data were not used because CTA-2045[5] load control events were occurring during that time frame.

Results

Baseline Load Shape

The 2018 baseline load shape for the 147 residential HPWHs is provided as a reference for the segmentation analysis in *Figure 1*. The HPWH power consumption profile demonstrates a dual-peaking curve, as shown in *Figure 1*. The morning peak occurs at the eighth and ninth hour of the day (i.e., 7:00 a.m. and 8:00 a.m.), while the evening peak occurs at approximately the 21st and 22nd hour of the day (i.e., 8:00 p.m. and 9:00 p.m.). The morning peak was the overall daily peak by a margin, but both peaks are comparable in their magnitude and duration. For the baseline load shape with an average of 2.9 occupants, the resulting HPWH energy consumption was 3,777 Wh, with a peak demand of 257 W.

Load Shape by Season (Impact of Inlet Air/Water)

As shown in *Table 1*, HPWHs were primarily installed in home garages (67%). For HPWHs installed in garages, entering air conditions to the HPWH would be impacted by outdoor conditions. Inlet water temperature also varies over the course of the year in the PNW. The segmentation of the data set by season (winter vs. summer) provides two extreme perspectives, with varying inlet air and water conditions.

In this study, summer was classified as June, July and August, while winter was classified as December, January and February. For the seasonal segmentation, only HPWHs that reported true power data (~80% of total) were included in the segmentation. The results of the seasonal segmentation shown in *Figure 2* demonstrate the magnitude difference between the seasonal extremes for the PNW. The electrical load profile of the HPWHs in the winter and summer indicate comparable morning and evening peaks, as well as a similar overall shape. For the seasonal load shapes, the resulting HPWH energy use was 5,063 Wh for winter and 3,048 Wh for summer, while the peak demand was 343 W for winter and 190 W for summer.

FIGURE 3 HPWH electrical load shapes by occupancy count.

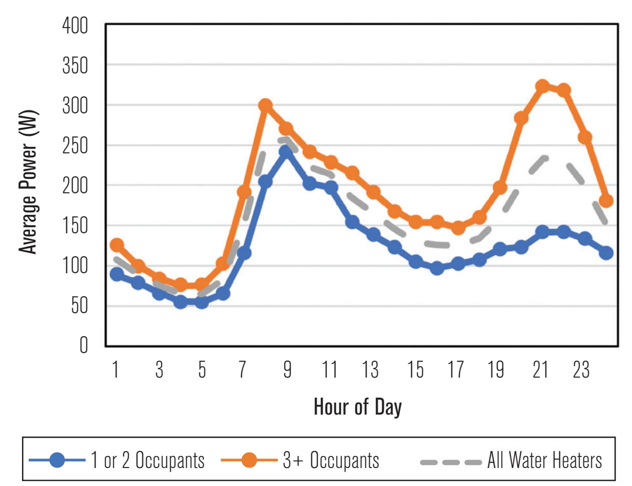
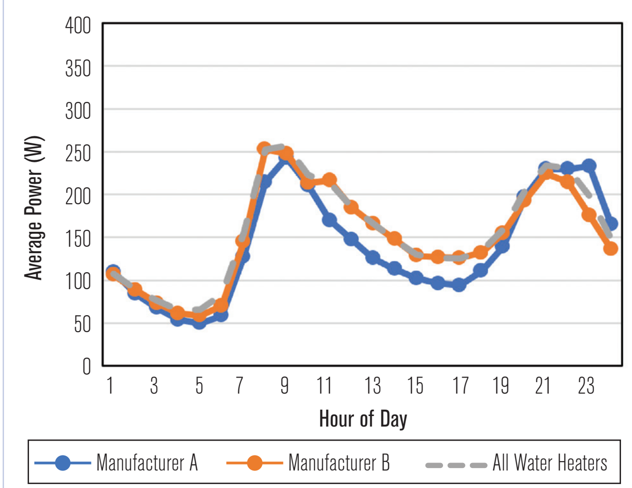


FIGURE 4 HPWH electrical load shapes by manufacturer.



Load Shape by Occupancy Count

In the homeowner survey, occupancy count was determined in whole increments for 1, 2, 3, 4 or 5+ occupants. For the segmentation analysis by occupant count, 1- to 2-person households and 3+-person households were grouped to provide a balanced sample count (72 vs. 75 sites) for comparison, as shown in *Figure 3*. The results of the segmentation by occupant are consistent with standard industry findings: increasing HPWH energy use and demand were observed with increasing occupant count.

An interesting observation from the occupant count segmentation resides with the electrical load profile. The 1- to 2-person aggregation resulted in a dominant morning peak, while the 3+ aggregation resulted in a relatively balanced morning and evening peak. For the occupancy count load shapes, the resulting HPWH energy use was 4,550 Wh for 3+ occupants and 2,997 Wh for 1 to 2 occupants, while the peak demand was 323 W for 3+ occupants and 242 W for 1 to 2 occupants.

Load Shape by Manufacturer

All HPWHs included in this study were CTA-2045 compatible and installed prior to data collection in 2018. The HPWH equipment models used were comparable in rated efficiency and nominal tank size between two manufacturers. A disparity in the HPWH brand or manufacturer existed across the field population, as one manufacturer accounted for approximately 80% of the field sites. A cluster of 16 field sites (one with Manufacturer A and 15 with Manufacturer B) were in colder, inland territory of the PNW and removed from the manufacturer segmentation analysis to eliminate this bias. The remaining sites were segmented by manufacturer to examine potential differences in operation.

As shown in *Figure 4*, the manufacturer segmentation analysis resulted in comparable load profiles, overall energy use and peak demand. For the manufacturer load shapes, the resulting HPWH energy use was 3,371 Wh, with an average of 3.0 occupants for Manufacturer A, while the HPWH energy use was 3,643 Wh, with an average of 2.8 occupants for Manufacturer B.

Load Shape by Occupancy Schedules

2018 Survey: Adult Home or Away

Each home's general occupancy schedule was determined in the survey by asking, "Does at least 1 adult not work outside of the home for 4+ days a week?" A "Yes" response indicates an adult was generally home, while a "No" response indicates the home was commonly unoccupied. The segmentation of the HPWH data set by occupancy schedule showed comparable home occupancy (2.9 vs. 3.1) and average HPWH energy use (3,893 Wh vs. 3,827 Wh); however, the load shape and peak demand had clear differences (*Figure 5*). The aggregated "Away" field sites demonstrated a more significant morning peak with minimal use during midday, while the aggregated "Home" field sites showed more balanced morning and evening peaks with greater relative use during midday hours. Additionally, the aggregated "Away" sites demonstrated a daily peak approximately 90 W higher than the "Home" segment of the HPWH population.

FIGURE 5 HPWH electrical load shapes by occupancy schedule.

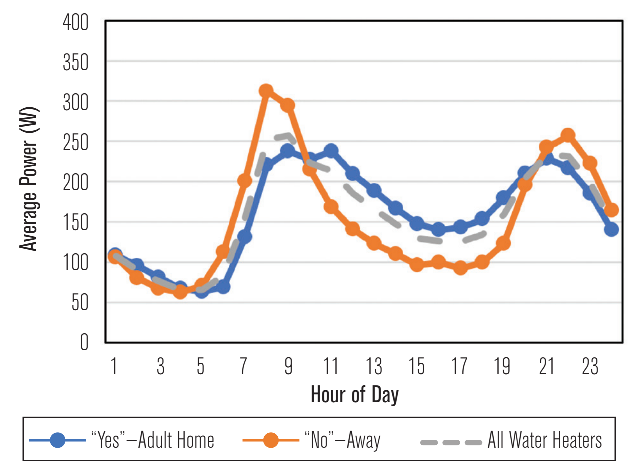
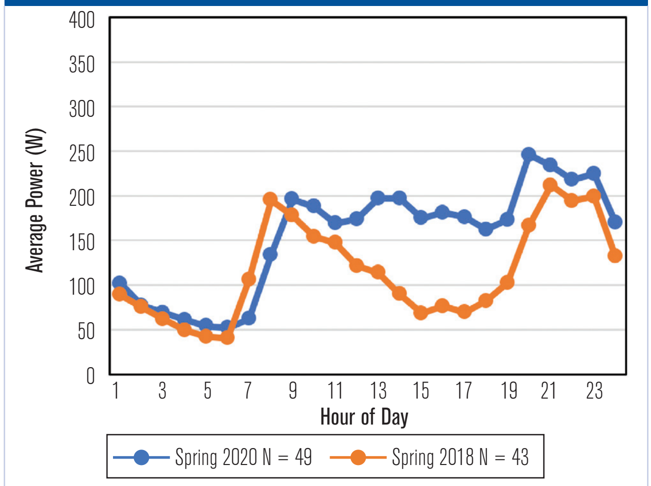


FIGURE 6 HPWH electrical load shapes for COVID-19 versus pre-COVID-19.



2020 COVID-19 Stay-at-Home Load Shape

During 2020, 49 sites in the Portland, Ore., area were still active in the field study during a regional stay-at-home order. *Figure 6* shows the Spring 2020 (COVID-19 stay-at-home) aggregated HPWH electrical load shape for the 49 sites and a load shape for the same field sites from Spring 2018 (pre-COVID-19) in which 43 of the 49 sites were active. For the Spring 2020 profile, it is likely that most field sites had an adult at home throughout the day due to the regional stay-at-home order. During Spring 2018, the occupancy schedule would be expected to generally align with the mix established in *Table 1*.

Pre-COVID-19 (Spring 2018) and stay-at-home (Spring 2020) HPWH load shapes demonstrate a significant shift in daily use (*Figure 6*). The pre-COVID-19 load profile was dual peaking (a.m. and p.m.), while the stay-at-home profile demonstrated a plateau load shape with more consistent HPWH electrical demand throughout the morning, afternoon and evening for the aggregated population. For the COVID-19 load shapes, the resulting HPWH energy use was 2,766 Wh for the pre-COVID-19 (Spring 2018) profile, while the HPWH energy use was 3,692 Wh for the stay-at-home (Spring 2020) profile.

Conclusion

Based on the 147 HPWHs included in the field study, the following trends were observed through the segmentation analysis of HPWH electrical load shapes:

- Occupancy schedule and occupancy count are primary drivers impacting the HPWH electrical load shape.
- Occupancy count and seasonal changes (inlet air and water conditions) are primary factors influencing HPWH energy consumption. The condition of the air entering a HPWH is impacted by its location in the home and the climate. Inlet water temperature, which varies over the year, impacts performance.
- Occupancy schedule, occupancy count and seasonal conditions (entering air and water conditions) are primary drivers for establishing the aggregate peak power demand of HPWHs.
- The regional COVID-19 stay-at-home period had a significant impact on the HPWH electrical load shape. The pre-COVID-19 load profile was dual peaking (a.m. and p.m.), while the COVID-19 stay-at-home profile demonstrated a plateau load shape with more consistent electrical demand throughout the day for the aggregated population.

References

1. NEEA. 2014. "Residential Building Stock Assessment: Metering Study." Northwest Energy Efficiency Alliance. https://tinyurl.com/y7jjhbxr

2. Pratt, R.G., et al. 1989. "Description of Electric Energy Use in Single-Family Residences in the Pacific Northwest—End-Use Load and Consumer Assessment Program." DOE/BP-13795-21. Pacific Northwest National Laboratory.

3. EIA. 2020. "Residential Energy Consumption Survey." Energy Information Administration. https://tinyurl.com/y2dfoo9d

4. Mayhorn, E.T. 2015. "Evaluation of the Demand Response Performance of Electric Water Heater." Pacific Northwest National Laboratory. https://tinyurl.com/ybjr8o92

5. CTA. 2018. "CTA-2045-A: Modular Communications Interface for Energy Management." Consumer Technology Association. https://tinyurl.com/yaxw4mam

6. State of Oregon. 2020. "Stay Home, Save Lives." Oregon Executive Order No. 20-12. https://tinyurl.com/yaq68qlv ■

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